AFRL-RV-PS-
TR-2013-0044

AFRL-RVPS-
TR-2013-0044

STORMTIME MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE INTERACTIONS AND DYNAMICS

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13 March 2013

Final Report

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From - To)***
13-03-2013	Final Report	14 Dec 2007 to 13 Dec 2012

4. TITLE AND SUBTITLE
STORMTIME MAGNETOSPHERE-IONOSPHERE-THERMOSPHERE INTERACTIONS AND DYNAMICS

5a. CONTRACT NUMBER FA8718-08-C-0012

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER 62601F

6. AUTHOR(S)
Patricia H. Doherty, William J. Burke, Frank Marcos, Susan Delay

5d. PROJECT NUMBER 1010

5e. TASK NUMBER PPM00004529

5f. WORK UNIT NUMBER EF004617

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Boston College
140 Commonwealth Avenue
Chestnut Hill, MA 02467

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/RVBXP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RV-PS-TR-2013-0044

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited. (377ABW-2013-0302 dtd 22 Mar 2013)

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Boston College has provided scientific and technical support to the Air Force Research Laboratory (AFRL) Space Vehicles Directorate for Stormtime Magnetosphere-Ionosphere-Thermosphere Interactions and Dynamics. The studies described in this report have leveraged our expertise on magnetosphere-ionosphere-thermosphere (M-I-T) coupling from high to low latitudes together with novel research to support AFRL's ongoing space weather missions aimed at characterizing the energy balance in the M-I-T system and forecasting realistically their responses to geomagnetic storms. The major studies address Magnetosphere-Ionosphere-Thermosphere coupling, magnetic storm studies, the development of a Dst proxy using DMSP measurements, satellite drag studies, an array of studies centered on the C/NOFS mission and the equatorial dynamics revealed by the C/NOFS measurements, and calibration/validation efforts for the DMSP SSULI and SSUSI sensors. This project resulted in over 20 publications in peer reviewed journals. These publications are discussed in this report and are referenced in the Reference section.

15. SUBJECT TERMS
MIT Coupling, Solar Wind, Equatorial Electrodynamics, Dst, C/NOFS, DMSP, Satellite Drag

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Dr. Yi-Jiun Caton
a. REPORT UNCLASSIFIED	**b. ABSTRACT** UNCLASSIFIED	**c. THIS PAGE** UNCLASSIFIED	Unlimited	28	**19b. TELEPHONE NUMBER** ***(include area code)***

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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1. INTRODUCTION

The Boston College Institute for Scientific Research (BCISR) has provided scientific and technical support to the Air Force Research Laboratory (AFRL) Space Vehicles Directorate for Stormtime Magnetosphere-Ionosphere-Thermosphere Interactions and Dynamics. The studies described in this report have leveraged our scientific expertise on magnetosphere-ionosphere-thermosphere (M-I-T) coupling from high to low latitudes together with novel research to support AFRL's ongoing space weather missions aimed at characterizing the energy balance in the M-I-T system and forecasting realistically their responses to geomagnetic storms.

This report provides a summary of the scientific and technical developments addressed under this contract. The major studies address Magnetosphere-Ionosphere-Thermosphere coupling, magnetic storm studies, the development of a Dst proxy using Defense Meteorological Satellite Program (DMSP) measurements, satellite drag studies, an array of studies centered on the Communication Navigation Outage Forecast Satellite (C/NOFS) mission and the equatorial dynamics revealed by the C/NOFS measurements, and calibration/validation efforts for the DMSP Special Sensor Ultraviolet Spectrographic Imager (SSUSI) and Special Sensor Ultraviolet Limb Imager (SSULI).

This project resulted in over 20 publications in peer reviewed journals. These publications are discussed in this report and are included in the Reference section.

2. BACKGROUND

The studies described in this report were performed in support of ongoing and planned space weather programs in the areas of Space Situational Awareness and Space Superiority. Our efforts include research in magnetosphere-ionosphere-thermosphere (M-I-T) coupling using data from DMSP, C/NOFS, ACE, and HAARP as well as measurements from future satellite missions of the Space Environmental Effects Monitoring System program to support operational space weather goals. Although current models provide reasonable estimates of space environmental conditions during quiet times, research has demonstrated the critical need for more accurate assessments of stormtime conditions during all phases of the solar cycle. The research we have performed addresses the specification and characterization of energy flow in the global M-I-T system to ultimately lead to forecasts of M-I-T responses to severe geomagnetic storms. It is during such intervals that the operational performance of DoD systems is most seriously tested.

At the start of this contract, AFRL was eagerly awaiting the launch of C/NOFS. The long delayed C/NOFS mission endeavored to nowcast and forecast ionospheric conditions that frequently plague communications, navigations, and surveillance operations. The results of the C/NOFS mission were expected to greatly enhance AFRL's space weather capability. Much of the work addressed in our report is dedicated to the C/NOFS mission. This includes modeling, data analysis, sensor validation and studies of equatorial electrodynamics. The results of these studies revealed many new and interesting phenomena related to equatorial ionospheric dynamics.

Other studies included research and technical support in several key areas in MIT coupling, I-T responses to geomagnetic storms, equatorial dynamics with the design and development of new space weather missions to meet the evolving challenges of operating in the near-Earth space environment.

3. METHODS AND PROCEDURES

For all of our studies, we relied on our prior scientific knowledge, the scientific literature, Boston College based computer programmers and analysts to assist with data processing and analysis. In addition, many of our studies were performed in collaboration with AFRL scientists insuring that the mission and goals of AFRL were always a key factor. Most of our efforts were disclosed at scientific meetings such as AGU, CEDAR, Chapman Conferences, Space Weather Conferences and internal seminars at AFRL and Boston College. Completed studies were summarized in publications in peer reviewed journals.

The following sections describe our major efforts. Each section contains multiple topics with each section including a description of the results and discussion.

3.1. Magnetosphere-Ionosphere-Thermosphere (MIT) Coupling

MIT coupling issues were addressed throughout the duration of this contract. Some of the early efforts were performed with analysis of input plasma and field data from the Advanced Composition Explorer (ACE) near the first Lagrange point (L_1) in the solar wind and responses observed by satellites of the Defense Meteorological Satellite Program (DMSP) and by accelerometers on the GRACE and CHAMP satellites in low-Earth orbit (LEO). The first and second studies combined plasma and magnetic field observations from L1 with measurements by the four CLUSTER satellites near the dayside magnetopause and in the magnetosphere by CRRES. The focus on the first study was the identification of signatures for tangential discontinuities in the solar wind and in the magnetosheath after the structure crossed the Earth's bow shock. Data were interpreted in the light of theoretical predictions and outcomes of magnetohydrodynamics (MHD) modeling. Our analysis identified the presence of predicted fast shocks that ride ahead of the discontinuity in the magnetosheath. Results are important for understanding the exact timing of dayside magnetosheath responses to changes in the solar wind. The second study analyzed the transmission of electric fields from interplanetary space into the magnetosphere and their effects on drift paths followed by energetic ions. The results of this research help modelers understand that electric fields penetration into the inner magnetosphere lasts for many hours, rather than a few minutes and demonstrates their affects of the locations of energetic particles in severe geomagnetic storms.

In October 2008, at the urging of Bruce Bowman (AFSPC), Dr. William Burke applied the new methods for estimating energy budgets of the stormtime thermosphere to neutral density perturbations measured by the GRACE satellite in response to high speed streams (HSS) in the solar wind. The driving HSS events were observed by the ACE satellite at L1 during the last four solar rotations in 2005. Indeed GRACE detected thermospheric heating events at the leading edges of HSS due to accompanying intensifications of the interplanetary magnetic field (IMF). Lower but measureable levels of thermospheric heating were also caused by large amplitude Alfvén waves embedded within the HSS structures. The investigation also revealed that the not only were HSS onsets and durations predictable using 195 Å images from the STEREO and SOHO satellites, so too were the polarity characteristics of the embedded IMF. The latter result offers a possibility of making reliable 27-day forecasts about the state of the thermosphere during periods of solar minimum when coronal holes and accompanying HSS events are common. While our model accurately predicted increases in global exospheric temperatures caused by Alfvén waves embedded within a HSS, it consistently over-predicted the observed thermospheric heating generated at its leading edge by ~ 30%.

A number of technical papers were prepared on MIT coupling research and all were accepted for publication [1, 2, 3, 4].

3.1.1. Magnetospheric Coupling to the Solar Wind/IMF

Dr. William Burke worked closely with Dr. Nelson Maynard in bringing to successful completion a study of solar wind interactions of the heliospheric current sheet (HCS) with the Earth bow shock and magnetopause. The primary tools were the ACE and Wind satellites in the solar wind and the Polar and cluster satellites in front of the dayside magnetopause. Magnetospheric responses were obtained using particle and field measurements from DMSP satellites. The ever-changing dynamics of the solar wind required great care in identifying features that appeared first in solar wind then magnetosheath data streams. The observed dynamics in the magnetosheath and magneto-sphere compared favorably with predictions derived from simulations using the Integrated Space Model.

This study compared high-resolution plasma and field measurements by ACE during the passage of the HPS/HCS with similar measurements by sensors on the Polar and CLUSTER satellites in the magnetosheath. Understanding the effects of the bow shock are important for two reasons: (1) The magnetosheath plasma and fields are presented to the magnetopause to drive the magnetosphere-ionosphere-thermosphere system, and (2) Passages of the HPS/HCS by Earth are highly correlated with high level of geomagnetic activity. The results of this research are published in [5].

3.1.2. Energy Flow in the MIT System

Using data from the Advanced Composition Explorer (ACE) satellite and the Gravity Recovery and Climate Experiment (GRACE) AFRL/RVBXP scientists continue to shed new light on the global dynamics of energy flow from the magnetosphere into the ionosphere and thermosphere during geomagnetic storms. Estimates of the polar cap potential (Φ_{PC}) and dynamic pressure of the solar wind (P_{SW}) based on the Siscoe-Hill model, and of the electric field (E_{VS}) based on the Volland-Stern model show promise as predictive tools. All three parameters, Φ_{PC}, P_{SW}, and E_{VS} increase significantly prior to storm onset. E_{VS} remains high throughout the main phase of each storm as the ring current is energized and Dst rapidly decreases to a minimum, then declines sharply preceding the end of the storm's main phase and beginning of recovery. Analysis of neutral densities inferred from measurements of accelerometers on GRACE satellites during the November 2004 magnetic storms yielded further proof that present satellite drag models under-predict stormtime density increases by >100%. Work was performed during this contract to upgrade operational models. DMSP F15 and F16 magnetic field data have been processed and sent to collaborators at the US Air Force Academy for a MURI project on neutral density and satellite drag.

3.1.3. Solar Wind Effects on MIT Coupling

This project involves understanding the effects of energy from the solar wind to the magnetosphere-ionosphere-thermosphere (MIT) system. The study focuses on the energy transfer from the solar wind during high-speed streams and corotating interaction region (CIR) with the coupled MIT system. We hope to understand the effects of both the initial compression of plasma and magnetic field associated with the CIR region and the effects of the extended high speed solar wind stream. Given specific dates, our first step was to create plots comparing thermospheric density responses measured by CHAMP and GRACE satellites as well as solar wind speeds and number densities measured by ACE/SWEPAM. Figure 1 illustrates our attempts to bring the observations together for further analysis by the scientific community.

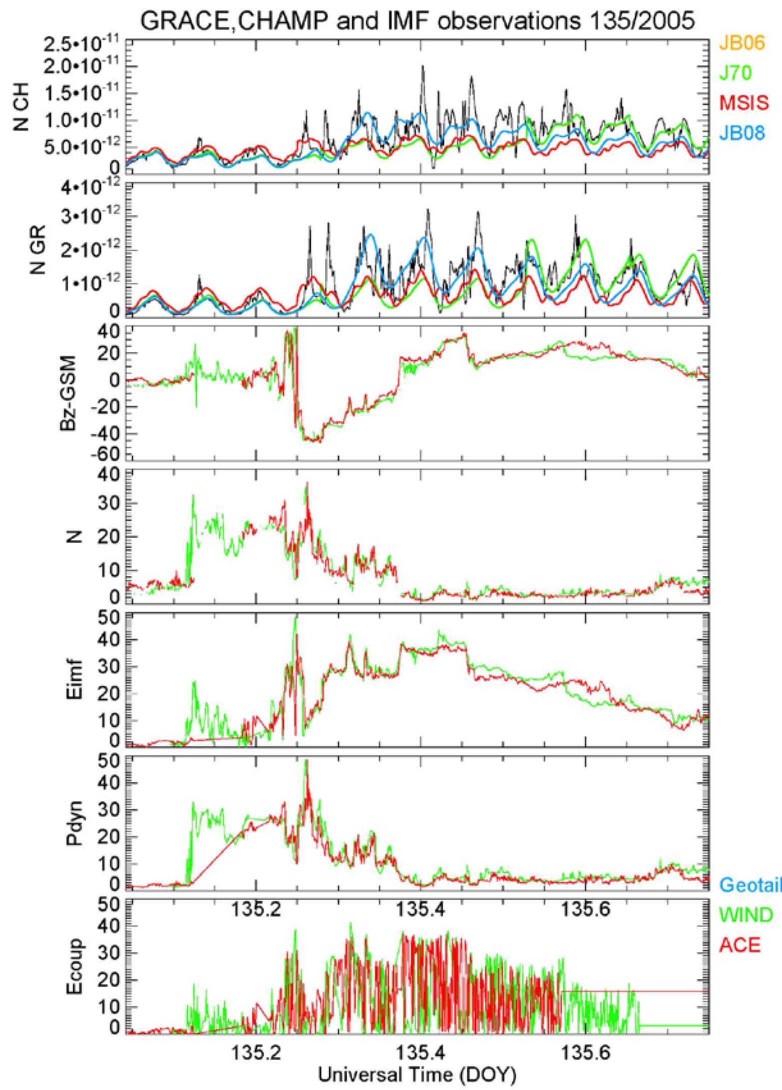

Figure 1. GRACE, CHAMP and IMF Observations on day 135, 2005.

3.2. Magnetic Storm Studies

3.2.1. Specifying Stormtime Dynamics of the Dayside Ionosphere

The purpose of this effort was to initiate on-going analysis of COSMIC-GPS measurements of total electron content (TEC) in the dayside ionosphere. Our general approach was as follows:

Phase shifts of two L-band signals emitted by Global Positioning Satellite (GPS) and received by sensors on the satellites of the COSMIC constellation are used to infer total electron content (TEC) along instantaneous paths between the spacecraft. Using an Abel transformation, sequences of these measurements are inverted to determine radial electron density profiles. These in turn are integrated to obtain vertical TEC. The present research concentrates on the dynamics of dayside TEC measurements acquired during a five-day period in which geomagnetic conditions went from quiet to disturbed and returned to quiet. TEC data show > 300% stormtime increases at mid latitudes (50^o to 70^o) near local noon. In the absence of auroral precipitation the data suggested that poleward transport was responsible. Analysis of plasma and field data from the Advanced Composition Explorer satellite near the first Lagrange point allowed estimates of magnetospheric electric fields and their mapping to the ionosphere. Consequent $E \times B$ plasma transport rates reproduce the main features of observed TEC variations favorably and compare favorably with predictions of the Thermosphere-Ionosphere Electrodynamic General Circulation Model (TIEGCM). Results of this effort were first presented by Ms Pei-Chen Lai at the *4th FORMOSAT-3/COSMIC Data Users Workshop* in Boulder, CO on 28 October 2009.

The effort took also address ways to incorporate new physical understanding into computer coding within the Thermosphere-Ionosphere Electrodynamic General Circulation Model (TIEGCM) and organizing the complex data inputs from multiple satellites such as ACE, SOHO, DMSP CHAMP and GRACE. Preliminary results of Ms Lai's work were presented orally to meetings of COSMIC Data Users and the Orbital Drag Environment (ODE) team at AFRL.

Full results of this research were published by Lai in 2011 [6].

3.2.2. Stormtime Electric Fields in the Low-latitude Ionosphere

A new technique was developed to extract electric fields in the equatorial ionosphere during major magnetic storms using drift meter measurements from the DMSP F13 satellite, which is in an 840 km circular polar orbit near the dawn-dusk meridian. Measurements were compared with electric fields measured upstream in the solar wind by the ACE satellite. The comparison allowed us to distinguish contributions from direct penetration of the interplanetary electric field, overshielding fields of magnetospheric origin and thermospheric dynamos. Being able to identify which fields are dominant at a given time will improve our ability to predict the formation of equatorial plasma bubbles and attendant scintillations of transionospheric radio signal. Results were published in the *Journal of Geophysical Research* [7].

3.2.3. Extreme Magnetosphere Forcing

On 20 November 2003, a few hours before the arrival of a magnetic cloud that caused the largest magnetic storm of solar cycle 23 the plasma sensor on the ACE detected sudden five-fold decrease in plasma pressure. Responses of the magnetosphere were monitored by the CLUSTER constellation near the dusk magnetopause and by the *Wind* satellite (at X_{GSE} = -221 R_E) that had been in the dawnside magnetosheath suddenly found itself inside the magnetopause beyond the distant neutral line. Within a few minutes the environment changed to that of a plasmoid moving ~700 km/s in the antisunward directions. Subsequent plasma and magnetic field observations indicate the Wind was sampling a highly unusual plasma and magnetic field environment. The observations were compared with predictions of the Integrated Space Model MHD code.

The simulations replicated plasma and field behaviors at Wind and CLUSTER and indicated that a near-Earth neutral line formed near lunar distance to create a large plasmoid the enveloped all of the nearby closed and open magnetic flux. The outer magnetotail was completely severed from its near-Earth counterpart. At the close of this contract, we continue to work on 2 papers that concentrate on CLUSTER and Wind observations and associated MHD simulations separately.

3.2.4. Globally-Averaged Exospheric Temperatures

In the development of a model for global thermospheric heating during magnetic storms W. Burke found it necessary to estimate the distribution of exospheric temperatures (T_∞) in local time. Through a visual inspection of T_∞ distributions embedded within the Jacchia's models, he concluded that polar-orbiting satellites should measure about the same orbit-averaged value of T_∞, independent of the local time of its orbital plane. While this perception led to vast simplifications estimating the energy content of the thermosphere, nagging questions remained about its validity. He and John Wise of AFRL devised and implemented two rather straight-forward methods to test the conjecture. Orbit-average values of T_∞ were calculated based on mass density measurements measured by the polar-orbiting GRACE and CHAMP satellites during two extended periods in 2003 and 2004 when their orbital planes were nearly aligned and at quadrature, respectively. Calculations were made in different ways and their results compared. To an amazing degree, correlation coefficients were consistently > 0.99, the analyses confirmed the basic assumption and even suggested new ways to improve estimates of atmospheric drag on space objects in low Earth orbits. A paper on this topic was published *Journal of Geophysical Research* [8].

3.2.5. Magnetopause Response to Rapid Changes in Solar Wind Pressure

Near mid-day on 20 November 2003 an interplanetary shock, characterized by large pressure changes in the solar wind arrived in the vicinity of Earth and produced the largest magnetic storm of the last solar cycle. The four-satellite Cluster constellation was flying near the magnetopause about 6 R_E behind the Earth. The pressure changes led to four crossings of the magnetopause in a 90 minute period, in a region seldom sampled by satellites instrumented to observe the electrodynamics associated with such crossings. Our study validated the large-scale correctness of an MHD model developed at Mission Research Corporations in the late 1990s. However, detailed analyses of energetic particle fluxes, electric field and magnetometer measurements from the four spacecraft identified regions at and near the magnetopause where MHD physics breaks down. This result has implications for the development of future computer modeling of the magnetosheath-plasma sheet interface in the near-Earth magnetotail. At the end of this contract, a paper on these results was accepted for publication in Journal of Geophysics Research in 2012 [9].

3.3. Development of a DST Proxy From DMSP Magnetometer Measurements

Research conducted by William J. Burke demonstrated that the main features of global thermospheric responses during geomagnetic storms can be obtained using the Dst index as the driving parameter. Because this advance has the potential for greatly improving precise trajectory calculations of objects in low Earth orbit (LEO) personnel from the Air Force Space Command (AFSPC) undertook a critical review that demonstrated Dst improves the accuracy of predicted atmospheric drag exerted on space objects tracked by AFSPC by > 25% and recommended that it be adopted in future operational programs. The review also recognized that Dst is a product of the University of Kyoto intended for research use only. Thus, a US based version of Dst should be pursued. In leading an effort to provide Dst based on magnetometer measurements by DMSP satellite Dr. Burke discovered that the simplest possible approach, using just variations of the Earth's field's horizontal component (ΔB_H) measured as DMSP crosses the magnetic equator provides an accurate estimate of both the Dst index and the degree of thermospheric heating due to magnetic storm activity. Results of this study were published in the *Journal of Geophysical Research* [10].

A related paper on stormtime heating of the thermosphere was also published in JGR [11].

In the course of this research it became apparent that using energy coupling coefficient derived to replicate GRACE measurements during magnetic storms in 2004, overestimated thermospheric heating observed in magnetic storms of 2005 – 2007. In the cited paper by [10] we presented *prima facie* evidence suggesting that this reflected diminished coupling due to low ionospheric plasma densities. During the recent quarter Dr. Burke analyzed 38 magnetic storms since the mid-2002 launch of GRACE for which measurements of the solar wind density and speed were available from the ACE satellite in halo orbit around the first Lagrange point L_1. The analysis showed that the coupling coefficient $\square_E$ of electromagnetic energy to stormtime thermosphere is highly ($R = 0.96$) correlated with the square root of the $F_{10.7}$ index. This parameter is widely used as a proxy for the EUV flux responsible for the production of ionization in the dayside ionosphere and thus the conductance of the upper atmosphere. Surprising, the coupling coefficient for the Dst index showed a similar, albeit weaker ($R \approx 0.7$), correlation with $\sqrt{(F_{10.7})}$. Reflection on the electrodynamics of interplanetary coupling to the stormtime magnetosphere removed much of the surprise, since ionospheric conductance impacts the electric fields that can be imposed on the magnetosphere and thus the energy content of the ring current.

To test the validity of this analysis, Dr. Burke applied the new coupling coefficients to the Halloween storm of 2003 using $F_{10.7}$ and Dst as the sole drivers. This very large magnetic storm was not among the 38 storms used to determine the solar-cycle dependence of coupling coefficients. Large fluxes of solar protons with MeV energies contaminated measurements by the plasma detector on ACE making it impossible to estimate solar wind densities during this storm. We were able to replicate thermospheric energies derived from GRACE measurements during all phases of this very large storm. Results were presented in two invited presentations at the

LANL/NASA sponsored *Theory of the Magnetosphere Workshop* in Santa Fe and in a University of Oslo, Department of Physics seminar in October 2010. A paper based on this research was published in JGR in 2011 [12].

Development of a DST Proxy Using C/NOFS

In May 2010, W. Burke gave an invited seminar at the NASA Goddard Space flight Center on the Dst proxy derived from DMSP/SSM data. Following the seminar, he discussed the possibility of deriving continuous measurements of Dst using the science grade tri-axial fluxgate magnetometer on the C/NOFS satellite in a low-inclination orbit, with Dr. Guan Le, the NASA PI for that sensor. Subsequently he outlined a series of procedures that may be implemented in near real time for her consideration. We have now agreed to initiate an informal cooperative alliance to implement a feasibility analysis for obtaining a C/NOFS-based Dst proxy. Interested Air Force and NASA personnel see this as a potentially significant step forward for specifying the energy states of the stormtime magnetosphere and global thermosphere, and consequently the atmospheric drag exerted on objects in low-Earth orbit during the coming decades.

During the spring of 2011 it became apparent the magnetometer data acquired by the C/NOFS satellite in a 13° inclined, low Earth orbit could be used to extract a useful proxy for the Dst index. This should be regarded as a follow-on to the previously reported DMSP-based Dst extraction paper. In both cases the correlation coefficient between the space-based methods and ground-based provisional Dst was about 0.97. However, the C/NOFS measurements also allow us to study the storm-time distribution of the ring current in local time. In December 2011, the results of this research were published in JGR [13].

3.4. C/NOFS Mission Support

The Communication/Navigation Outage Forecasting System (C/NOFS) satellite was launched on 16 April 2008 after a long delay. It was launched on a Pegasus rocket carried aloft by an L10-11 aircraft from Kwajalein Island. Over the course of the following month, all spacecraft instrumentation was turned on successfully and all sensors were deemed operational. The C/NOFS prime mission was to nowcast and forecast ionospheric conditions that frequently plague operational communication, navigation, and surveillance systems.

Under this contract, BC staff members supported the C/NOFS mission in a number of ways. They participated in planning, monitoring, research and calibration and validation efforts throughout the duration of this contract. The prime motivation for this support under this contract was to be able to utilize the C/NOFS mission to support our studies of Stormtime Magnetosphere-Ionosphere-Thermosphere Interactions. The following highlights some of these efforts.

3.4.1. Comparing the DMSP EPB Climatology with PBMOD

In preparation for the launch of the C/NOFS satellite, evening sector observations of plasma density depletions by sensors on DMSP spacecraft were used to develop a global climatology of equatorial plasma bubble (EPB) occurrence by season and longitude. DMSP observed most EPBs near the equinoxes in the spring and fall in the American-Atlantic-African sector in all phases of the solar cycle. Following this effort, we then tried to simulate these observations using PBMOD, a first-principles model of the ambient ionosphere and bubble formation, using climatological drivers. We compared maps of the model calculations of EPB rates at 840 km altitude as a function of season and longitude with the DMSP observations. These maps show the expected peaks in frequency of EPBs near the equinoxes, with the additional winter peak in the American sector and the summer peak in the Pacific sector. We also compared EPB rates from several DMSP spacecraft with the model results during various phases of the solar cycle and found good agreement during solar maximum and in transition years as well, although the model probabilities were generally higher than the observations. Model results for solar minimum conditions showed more intense features during equinox months that did not match observations. Adjustments in the plasma drift velocity models used in PBMOD eliminated those features and helped to fine tune the models for the C/NOFS mission. A presentation was given at the C/NOFS Engineering Working Group #9 and Science Meeting that was held at the University of Texas at Dallas on 18-20 March 2008. A similar presentation was given at the Ionospheric Effects Symposium 2008 in Alexandria, Virginia, on 13-15 May 2008.

3.4.2. Equatorial Electrodynamics and the C/NOFS Mission

Equatorial electrodynamics has been a major focus of AFRL/RVB for the last decade to which Boston College personnel have made significant contributions. Based on DMSP plasma density measurements, results in [14] were the first to point out that intense equatorial plasma bubble activity intensifies during the main phase of magnetic storms. However, it is completely absent from observations at topside altitudes for 3 to 4 days into the recovery phase. This happens even during times when it normally is present in abundance. Main phase activity was explained as a result of electric field penetration from interplanetary space. This explanation is now universally accepted. The subsequent absence was attributed to a stormtime wind system called the disturbance dynamo. Time scales for thermospheric recovery observed after interplanetary electric fields quiet this explanation implausible. We address the question: “Why is the dayside dynamo unable to generate equatorial plasma bubbles for several days into recovery?” During solar maximum EUV power from the Sun of ~500 GW drives the dayside thermosphere. We argue that growing evidence suggests that fossil winds and displaced thermospheric distributions of molecular species are at the root of this mystery. Understanding the recovery phase dynamics is of critical importance for predicting ionospheric plasma disturbances that disrupt Air Force communications and navigation capabilities at low latitudes during evening local times. This work has significant relevance for the C/NOFS mission.

C/NOFS supports its mission by developing new capabilities for predicting the growth of equatorial plasma bubbles whose attendant density irregularities scatter radio waves propagating in the low-latitude ionosphere. The irregularities reflect instabilities that originate in the nightside ionosphere at altitudes below the peak of the F-layer. The instabilities are caused by eastward electric currents reflecting differential electron and ion drifts in response to local electric fields. Measurements from the vector electric field instrument (VEFI) and planar Langmuir probe (PLP) on C/NOFS provide input/response information needed to understand the generation and dynamics of the nightside equatorial ionosphere.

In the first 2 years of this contract, BC personnel illustrated the results of their research in the three papers on ionospheric electrodynamics that were published in a special issue of *Geophysics Research Letters* on C/NOFS measurements. These studies addressed four specific tasks: (1) causes of eastward electric fields at low latitudes [15], (2) validation of the AFRL model for predicting equatorial disturbances [16], and (3) dynamics of deep plasma depressions generated near the dawn meridian [17].

Later work performed by BC personnel also utilized C/NOFS measurements to detect broad plasma depletions in the post midnight-dawn sector. As part of this effort, Dr. C.S. Huang searched the C/NOFS data over a 2.5 year period and found a number of cases. The broad depletions start to occur in the evening sector, become very deep after midnight, and cover a longitudinal range of 20-40 degrees (2000-4000 km). A very unusual feature is that strong upward ion drift velocity (200-400 m/s) occurs inside the depletion region. The broad depletions with strong upward ion drift are completely different from the dawn plasma density decreases with small downward ion velocity. We have proposed a new mechanism to explain the generation of the broad depletions with upward ion drifts. In this mechanism, multiple plasma bubbles are caused by the Rayleigh-Taylor instability in the evening sector, grow to large size in the postmidnight sector, and then merge into broad plasma depletions. The broad plasma depletions result from merging of multiple regular equatorial plasma bubbles. This mechanism reveals the relation between equatorial plasma bubbles and broad plasma depletions and can well explain the observations of isolated plasma bubbles, multiple separated bubbles, wide plasma bubbles, and broad plasma depletions. This study significantly increases our understanding of the low-latitude ionospheric electrodynamics and disturbances during solar minimum. A paper on this topic has been published in the Journal of Geophysics Research [18].

Much effort has been expended to validate the C/NOFS data with ground-based GPS measurements of TEC. Figure 2 illustrates data that was collected in South America in 2008 by the Low-latitude Ionospheric Sensor Network (LISN) network of GPS receivers together with measurements from 3 other networks belonging to Ohio State University, IGS and SIRGAS. The left frame of the figure displays the measured TEC values at the ionospheric intersection point. The right frame shows smoothed TEC values that were obtained after a running fitting algorithms is applied to the measured TEC values. This database has been a valuable tool to compare and validate measurements and assess the day-to-day variability of the regional distribution of TEC over South America and find its dependence as a function of the season, solar flux, and magnetic conditions. Figure 2 shows an exceptional event in which a large longitudinal variability in the location of the crests of the anomaly was found over SA. There exists a single northern peak on the western side of South America and a single southern peak on the eastern side of South America.

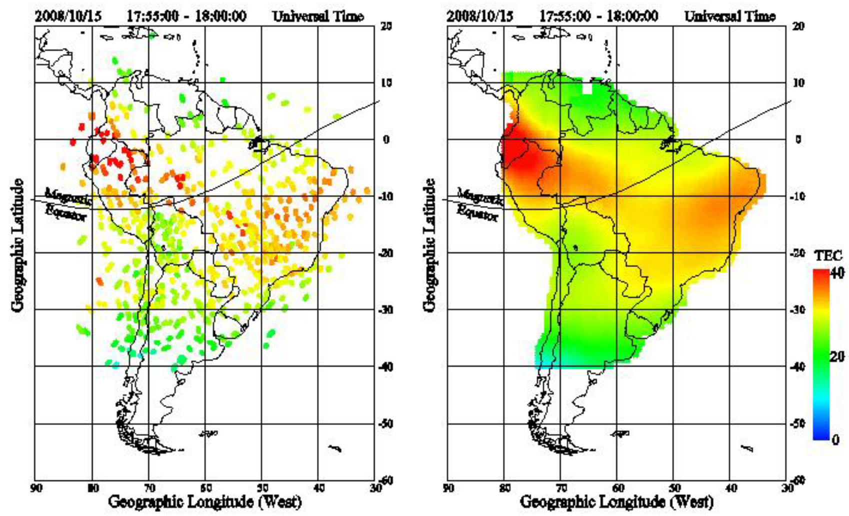

Figure 2. LISN TEC showing longitudinal variability of the crest of the anomaly.

3.4.3. Electric Field Plasma Depletions in the Low-latitude Ionosphere

Working with colleagues at the Goddard Space Flight Center, Dr. Burke helped write a paper describing vector electric field measurements by the C/NOFS satellite during a 90-day centered near the June 2008 solstice. The study shows that electric field distributions near solar minimum are qualitatively very different from their solar maximum counterparts. Features like the pre-reversal enhancement thought to drive equatorial plasma bubble (EPB) activity in the dusk local time sector are simply not present. This is consistent with measurements by plasma detectors on the DMSP and C/NOFS satellites that show almost no encounters with EPBs at pre-midnight local times during the present deep solar minimum. The study also revealed unsuspected longitude dependence in the distribution of near equatorial electric fields. While we suspect that this is caused by non-migrating thermospheric tides, identifying its cause will be pursued is a later study. The paper was published in the December 2010 issue of the *Journal of Geophysical Research* [19].

A study related to this topic was also completed regarding the season-longitude climatology of plasma depletions observed in data acquired by the cold plasma sensor on DMSP F17 whose descending node in near the 05:30 local time meridian. In previously reported studies we noted that F17 generally crossed equatorial plasma depletions observed with the planar Langmuir probe on the C/NOFS satellite. F17's circular, sun-synchronous orbit takes altitude and local time dependencies out of play and allows this climatological study. Our analysis shows that during this and the previous solar minimum: (1) Dawn-sector depletions occur most frequently near the solstices, rather than near the equinoxes as seen for equatorial plasma bubbles in the evening sector. (2) Occurrence frequencies for dawn-sector depletions are heavily weighted in favor of longitudes with large land masses (South America, Africa and India/Indonesia). (3) Annual occurrence rates are inversely proportional to yearly-averaged values of $F_{10.7}$. The second and third results are consistent with the longitudinal distribution of pre-dawn electric fields and the dearth of dayside electric fields [19] required to drive the dayside dynamo. A report on our results was accepted for publication in the *Journal of Geophysical Research* [20].

3.4.4. Mapping Plasma Density Irregularities

A survey of solar minimum data records shows very few examples of depletions with longitudinal widths of several tens of kilometers were reported in studies at post-sunset local times. However, bottomside irregularities still occur in the evening sector where they induce scintillations of trans-ionospheric radio and GPS microwave signals. Within the C/NOFS database examples of such structures abound in the post-midnight to dawn local time sector. Within such depletions eastward polarization electric fields (upward δV_V) characteristic of EBS are identifiable in VEFI measurements. However, when we examined pre-midnight PLP data streams at milli-second resolution a different picture emerges. On these shorter spatial/temporal scales the topside plasma observed by CNOFS, above regions where scintillations are reported on the ground, can appear quite turbulent. A preliminary survey shows a positive correlation between δn and δV_V measurements. We have performed Fourier transformations on 3-second segments of data. In the few samples studied to date, when C/NOFS was in close temporal and spatial proximity to the ground stations reporting strong scintillation activity, the Fourier analyses showed significant power at scale sizes between 0.1 and 1 km. With available C/NOFS technology it is not possible to specify the spectral distribution of irregularities present in the bottom side of the F layer directly. However it is known that the bottomside irregularities must have significant power at the Fresnel scale size to produce strong scintillations. The Fresnel scale ($\sqrt{2\lambda d}$) for phase-screen irregularities near $d = 300$ km to produce scintillations of 250 MHz signals ($\lambda = 1.2$ m) is ~0.85 km. This is a spectral region of high power in topside irregularities measured during C/NOFS over flights of ground station experiencing strong scintillation activity.

We have examined the possibility that the PLP detect mappings of bottomside irregularities into the topside. The study proceeded has established:

(1) An empirical and theoretical relationship exists between δn, δV_Z and AC electric field variations observed by VEFI during over-flights of ground stations where scintillation activity is positively identified. Polarization electric fields associated with the formations of bottomside irregularities appear to map the higher altitudes where they distort local plasma distributions. In this mapping, δn decreases at bottomside altitudes correspond to increases in the topside ionosphere.
(2) These observed relationships provide the basis for developing methods to remotely indentify the presence or absence of scintillation-causing irregularities on the bottomside of the F layer from plasma density signatures monitored at topside altitudes.

Results of this study were presented at the *Space Weather Week* meeting in Boulder, Colorado during April 2011. This study was entitled “Two kinds of plasma density irregularities observed at topside altitudes”.

3.4.5. Longitudinal and Seasonal Dependence Observations

During the night in the F region about the equator, plasma density depletions form, causing scintillation. In April 2008, the Communications/Navigation Outage Forecasting System (C/NOFS) satellite developed by the Air Force Research Laboratory was launched to predict ionospheric scintillation. Using its Planar Langmuir Probe (PLP), C/NOFS is capable of measuring in situ ion density within the F region over the equator. Plasma irregularities are found regularly during the night. This research examined how these irregularities depend on longitude, latitude, and season. The most significant observations from this study are longitudinal structures in which these irregularities most frequently occur. Since similar structure has been found in diurnal tides, we conclude that lower atmospheric tides may play a strong role in determining the amplitude of equatorial irregularities, at least during low solar minimum conditions when the presented observations were made. The conclusion of this effort is that this this link is likely related to the generation of zonal electric fields by the E-region dynamo. This work is reported in [21].

In early October 2008, the C/NOFS satellite orbited near the magnetic equator at its perigee altitude of ~400 km at dusk in the Peruvian sector. This provided an ideal opportunity for a comparison, under the current very low solar flux condition, of equatorial ionospheric disturbances observed with the Communication/Navigation Outage Forecasting System (C/NOFS) in situ measurements and ground-based observations available near Jicamarca Observatory. The primary objective was the comparison of plasma density disturbances measured by a Planar Langmuir Probe (PLP) instrument on the C/NOFS satellite with VHF scintillation activity at Ancon near Jicamarca for this period. Here we discuss in detail two extreme cases: one in which severe in situ disturbances were accompanied by mild scintillation on a particular day, namely, 10 October while there was little in situ disturbance with strong scintillation on 5 October. This apparent contradiction was diagnosed further by a latitudinal ground-based GPS network at Peruvian longitudes, a Digisonde, and the incoherent scatter radar (ISR) at Jicamarca. The crucial distinction was provided by the behavior of the equatorial ionization anomaly (EIA). The EIA was well-developed on the day having severe in situ disturbances (10 Oct). This led to lower equatorial plasma density and total electron content (TEC) at the equator and consequently reduced the scintillations detected at Ancon. On the other hand, on the day with severe scintillations (5 Oct), the EIA was not so well developed as on 10 October, leading to relatively higher equatorial plasma density and TEC. Consequently the severe scintillations at Ancon were likely caused by ionospheric structure located below the altitude of C/NOFS. The NRL SAMI2 model was utilized to gain a greater understanding of the role of neutral winds and electric fields in reproducing the TEC as a function of latitude for both classes of irregularities. Spectral studies with high resolution in situ PLP data were also performed. The power law spectra within the plasma bubbles showed two slopes: the low frequency slope being $\sim -5/3$ and the high frequency ~ -5 with a break around $\lambda = 70$ m. This particular type of two-slope spectra may be related to the extremely low solar activity and its impact on ion composition and temperature. This research has been reported in [22].

3.4.6. C/NOFS Sensor Validation

Work was performed to analyze the ion densities measured by the Planar Langmuir Probe (PLP) on C/NOFS. At first all of the PLP data was considered (pt per second). Upon reflection, it was decided to do 60 second averages. The densities were detrended and scaled using the International

Reference Ionosphere (IRI) model. Once scaled, the data confirmed the Broad Plasma Decreases in the South Atlantic Anomaly lasting up to six hours and decreasing by a factor of 2. The decreases are separate from the bubbles or depletions.

This work was presented in the April 2008 at the C/NOFS meeting and in June 2008 at the Beacon Satellite Symposium. The purpose of this effort was to analyze the spacecraft observations of plasma decreases in the equatorial ionosphere during June Solstices and solar minimum. Our results showed that even during solar minimum, the ionosphere presents surprising challenges to accurate modeling and forecasting.

Work continued on error analysis of the ion densities measured by the Planar Langmuir Probe (PLP) on C/NOFS. This analysis focused on the Dec08-Jan09 period. The results displayed an effect where the data points are wildly erratic just about when the event was about to start. This finding prompted AFRL to provide a new data set with a correction constant which is used to multiply the original densities to get the corrected densities. From about June/July 09 onwards, this number should be 1. There were problems with the new data as well. These findings were reported to AFRL and they illustrate BC's efforts to validate the C/NOFS PLP sensor. A paper was presented at the 2010 AGU fall meeting.

3.5. Satellite Drag Studies and Data

3.5.1. TIEGCM Model

BC staff members have assisted AFRL's long term goal of transitioning an operational version of a physics based satellite drag model. The impetus is to capture the major error source in orbit prediction and the spatial/temporal variations in neutral density driven by geomagnetic storms. Empirical models are limited in their ability to describe these perturbations. BC staff members have helped map out a Tech Transition Plan.

Large yearly databases (2002-2010, ~0..5M points/year) giving satellite accelerometer data vs. physical and empirical models are being generated at AFRL. Initial work focused on determining additional parameters needed in the database and identifying and removing bad data points.

One objective of AFRL studies being supported is correcting semiannual variation model errors by incorporating a variable eddy diffusion coefficient at the model lower boundary. Then geomagnetic storms can then be more fully addressed. BC team members noted an apparent local time asymmetry in the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIEGCM) predictions vs. CHAMP satellite data that needed to be addressed to appropriately interpret model corrections e.g. orbit averaged data will not best for determining model corrections since 2 local times are involved on each orbit.

Further efforts under this topic included a presentation by Mr. F. Marcos that included statistical analysis of TIEGCM to CHAMPS vs. solar flux. In this effort, Mr. Marcos identified that the CHAMP data contained bad data points. He also noted that TIEGCM consistently underestimated neutral density geomagnetic response for large storms. His results were included in a paper presented by Dr. Chin Lin on "Validation of low altitude neutral density modeling" at the Chapman Conference on Modeling the Ionosphere/Thermosphere System in Charleston, S.C. in May 2011.

3.5.2. Normalization of GRACE and CHAMP Neutral Density Measurements

Many ongoing scientific analyses of thermospheric responses to solar and geomagnetic influences rely on measurements from accelerometers on the polar-orbiting CHAMP and GRACE satellites. While relative changes, thermospheric densities and temperatures are understood, their absolute values are not. A 2008 study at AFSPC demonstrated that the present calibrations of the CHAMP and GRACE accelerometers are irreconcilable with one another and suggested that they be normalized to outputs of the High Accuracy Satellite Drag Model (HASDM).

Dr. Eric Sutton, University of Colorado, addressed the fundamental aerodynamics underlying calculations of atmospheric densities and wind speeds from measured drag accelerations measured by CHAMP and GRACE. Data derived from Sutton's calculations were made available on a U. Colorado web site and were analyzed by Dr. John Wise of AFRL and Dr. Burke and Ms. Delay of Boston College. Together they completed a survey of changes to CHAMP/GRACE parameters derived using the AFSPC method.

In the course of our analyses we found that energy coupling between the solar wind and the thermosphere inferred for the magnetic storms of 2004 exceeded that observed during the magnetic storms of the subsequent solar minimum period. This led us to postulate that our derived energy-coupling coefficient has a solar-cycle dependence. At the request of a Referee, we demonstrated the physical existence of this dependence in the revised manuscript of *Burke, et al.*, "Estimating Dst Indices and Exospheric Temperatures from Equatorial Magnetic Fields Measured by DMSP Satellites." WJB recently initiated a related effort to quantify this dependence by examining exospheric temperatures changes inferred from orbit-averaged thermospheric densities measured by accelerometers on the GRACE and Champ satellites during all magnetic storms for which data are available between mid-2001 (when Champ was launched) and the end of 2009. Amassing and analyzing the consequent large database are significant undertakings that have continued throughout much of this contract.

3.6. Calibration/Validation of DMSP SSUSI and SSULI Sensors

BC personnel have supported AFRL's participation in the Calibration/Validation (cal/val) of the DMSP F-18 SSULI (Special Sensor Ultraviolet Limb Imager) Neutral Density Profiles (NDP's). F. Marcos supported development of a more detailed cal/val plan requested by the SPO. Work involved inputs to a timeline with major milestones as well as roles and responsibilities. Specific areas included defining interactions between AFRL, NRL and Aerospace Corp analyses approach from in-situ data, orbital drag and remote sensing. Tasks also included SSULI evaluation techniques using long-term statistics, coincidence measurements and isolated geomagnetic storm case studies.

F. Marcos supported development of overall strategy. The fundamental errors in measuring drag by accelerometers, Special Perturbations, Two-Line Element sets and HASDM were examined to help establish ground-truth for SSULI comparisons when the data become available. Mr. Marcos also supported discussions on the feasibility of using RAIDS data to correct HASDM temperatures. Numerous anomalies are found in CHAMP-GRACE comparisons with each other and with orbital drag. These were studied in coordination with NRL and Aerospace Corp.

Additional work was performed on the SSULI neutral density validation along with an ongoing ground truth inter-comparison study. The approach is to acquire the SSULI neutral EDRs, process and analyze one year of data using ground truth and coincidences. The ground truth data includes HASDM orbit-based drag, CHAMP accelerometer data, GRACE accelerometer data and empirical models, Jacchia70, JB06,Jb08 and MSIS. CHAMP/HASDM and GRACE/HASDM biases and standard deviations have been completed. The bias levels are generally in good agreement. Conjunctions were found between the ground truth data and the drag data.

Work was also performed on the validation study of the SSUSI Total Electron Content (TEC) derived from the SSUSI disk UV measurements. This study compares the derived TEC data with the vertical TEC deduced from the dual-frequency radar altimeter onboard the JASON-1 satellite. During this quarter, new SSUSI and JASON data was received. After processing the JASON data, it was clear that the algorithm used for F17 would no longer be consistent because there were errors in the JASON header data. A new algorithm was written and the JASON data was unpacked. Sarah McDonald of NRL supplied a sample set of the SSULI data. The SSUSI data that was unpacked included day and night disk data as well as night limb data. Two TEC values from different algorithms were found on the day disk data files. The other data files contained NMF2 from which a TEC value could be determined.

It was discovered that when using the local time as one of the conjunction constraints (as was done with F17), it was possible to find double conjunctions from one JASON pass to two SSUSL revs. It was then determined to use UT as the time constraint for the conjunctions. The constraints agreed upon are: ±12˚ longitude, ±5˚ latitude and 30 minutes for UT. A bias for the JASON TEC was set at 5 TECU. Figure 3 shows examples of a night limb DMSP F18/JASON (on the left) and the SSULI/JASON conjunctions (on the right).

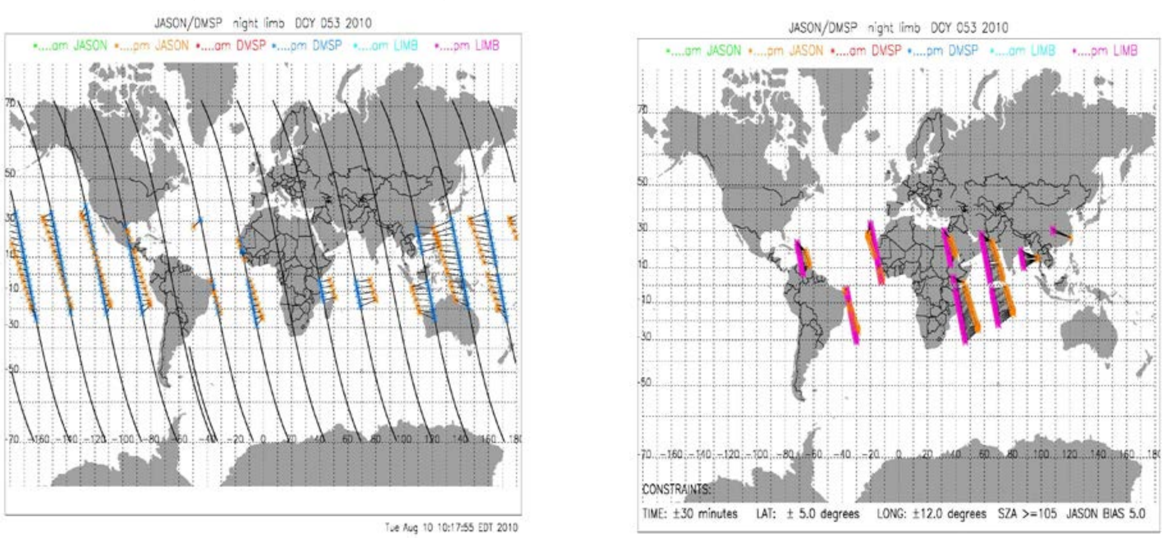

Figure 3. Night limb DMSP F18/JASON conjunctions with SSULI/JASON conjunctions.

3.7. New Space Weather Satellite Missions

The last Defense Meteorological Satellite Program (DMSP) spacecraft is scheduled for launch within the next 4-5 years. At the time of this report, there are still no definite plans for new space weather missions after DMSP, although several options are under consideration. Since it is extremely difficult to find funding for dedicated missions, AFSPC is considering taking advantage of rides of opportunity on spacecraft launched by other agencies. This has financial advantages, but limits sensor and orbit options and does not provide the space weather capability required for the Space Situational Awareness mission. Boston College has support AFRL in developing plans for future polar and equatorial orbiting satellites with comprehensive and complementary suites of space weather sensors that are needed to provide continuity of space environmental monitoring after DMSP and C/NOFS. The long-term datasets provided by DMSP have proved to be a critical component of the US Space Weather Program and must be maintained. To support this effort, a poster describing some of the recent research using DMSP data that is contributing directly to operational missions was presented during the Operational Space Weather Special Session at the Fall AGU meeting in December 2008 in San Francisco.

In summer of 2009, Boston College personnel prepared a report on the need for an AFRL flight of an accelerometer on CubeSat for Dr. Chin Lin submission to RVS. The report included relevance, thermosphere variability, state of current models, instrumentation (the miniaturized accelerometer being developed under SBIR), orbit requirements and benefits to be derived. Inputs on attitude control and aerobraking from Eric Sutton and their mission impact were added. It was completed on schedule, 30 September and was rated “excellent” by RVS. This report was then made available as an AFRL Tech Report with limited distribution since RVS plans to provide it to potential contractors.

Boston College continued mission support for flying small satellite accelerometers to measure neutral density and winds. This included reviewing specs for instruments being developed under an SBIR. One instrument is being developed for RVS to measure drag on a system of CubeSats. Another instrument is anticipated to be flown together with a larger “heritage” AFRL mass spectrometer and winds payload. These instruments would provide a calibration of the new miniature accelerometer.

BC scientific staff members participated in several teleconferences with Chin Lin, Eric Sutton and RVS on experiment status and flight operations plan. RVS suggested a back-up plan in the event that the SBIR accelerometer did not meet its goal. Discussions were held with accelerometer SBIR contractor to evaluate potential alternate design benefits of a Georgia Tech small accelerometer. It was decided to not follow this alternative and to keep working with the present configuration. BC personnel advocated, as an alternative, a CubeSat-compatible NASA experiment that measures relative density, composition and winds. This led to a MIPR being developed between AFRL and NASA Goddard Space Flight Center for this experiment. The plan is to initially fly it as part of the Air Force Academy Falconsat 6 satellite.

Further support on this topic was performed by F. Marcos by describing the design of the spacecraft support needed for this mission. At their initial design review, Boeing stated that they can launch four CubeSats with AFRL payloads and provide the needed power, commands and attitude data. F. Marcos also participated in Creare's Critical Design Review for a Phase 2 SBIR small accelerometer for this mission. It is not obvious that they will have a compatible instrument in time for launch. The NASA GSFC sensor originally advocated for this mission is now a candidate back-up.

4. CONCLUSIONS

Over the five-year span of this proposal, Boston College performed distinctive research in support of the AFRL Space Vehicles Directorate mission and goals related to Stormtime Magnetosphere-Ionosphere-Thermosphere Interactions and Dynamics. This report concludes that the results of the scientific studies described contributed significantly to the state of knowledge on MIT coupling, magnetic storms, satellite drag and equatorial electrodynamics. Staff members participated in all aspects of the C/NOFS mission including planning, modeling, sensor and data validation and data analysis. Boston College was also instrumental in AFRL plans and designs for new space weather satellite missions including a miniaturized accelerometer that can be flown on CubeSats. A major product of our efforts is a new proxy for Dst from DMSP measurements. Boston College also supported calibration and validation efforts for the DMSP SSUSI and SSULI sensors.

The efforts of the Boston College personnel supporting this contract have produced more than 20 papers in referred journals. Boston College personnel also presented the results of this research at professional conferences and internal presentations at AFRL and Boston College.

REFERENCES

[1] Burke, W. J., Stormtime energy budgets of the global thermosphere, in Mid-Latitude Ionospheric Dynamics and Disturbances, edited by P. M. Kintner, A. J. Coster, T. Fuller-Rowell, A, J. Mannucci, M. Mendillo, and R. A. Heelis, *American Geophysical Monograph 181*, Washington, DC, 235-246, 2008.

[2] Burke, W. J., C. Y. Huang, D. R. Weimer, J. O. Wise, G. R. Wilson, C. S. Lin, and F. A. Marcos, Energy and power requirements of the global thermosphere during the magnetic storm of November 10, 2004, *J. Atmos. Solar-Terr. Phys*., 2008.

[3] Huang, C. Y., W. J. Burke, and C. S. Lin, Two observed consequences of penetration electric fields, *J. Atmos. Solar-Terr. Phys*., doi:10.1016/j.jastp.2008.09.018, 2008.

[4] Burke, W. J., C. S. Lin, M. P. Hagan, C. Y. Huang, D. R. Weimer, J. O. Wise, L. C. Gentile, and F. A. Marcos, The stormtime global thermosphere: A driven-dissipative thermodynamic system, *J. Geophys. Res.*, 114, doi:10.1029/2008JA013848, 2008.

[5] Maynard, N. C., C. J. Farrugia, W. J. Burke, D. M. Ober, J. D. Scudder, F. S. Mozer, C. T. Russell, H. Rème, and E. Lucek, Interactions of the heliospheric current and plasma sheets with the bow shock: Cluster and Polar observations of magnetic field variations in the magnetosheath, *J. Geophys. Res.,* doi:10.1029/2010JA015349, 2010.

[6] Lai, P.-C., C. S. Lin, W. J. Burke, C.-M. Huang, and M.-Q. Chen, COSMIC observations of dayside total electron content enhancements in response to moderate disturbances in the solar wind, *J. Geophys. Res*., 116, A05318, doi:10.1029/2010JA015772, 2011.

[7] Huang, C.-S., F. J. Rich, and W. J. Burke, Storm time electric fields in the equatorial ionosphere observed near the dusk meridian, *J. Geophys. Res.*, 115, A08313, doi:10.1029/2009JA015150, 2010.

[8] Wise, J. O., W. J. Burke, and E. K. Sutton, Globally averaged exospheric temperatures derived from CHAMP and GRACE accelerometer measurements, *J. Geophys. Res.*, 117, A04312, doi:10.1029/2011JA017108, 2012.

[9] Maynard, N. C., C. J. Farrugia, W. J. Burke, D. M. Ober, F. S. Mozer, H. Rème, M. Dunlop, and K. D. Siebert, Cluster observations of the dusk flank magnetopause near the sash: Solar wind/IMF control, ion dynamics, and flow through reconnection, *J. Geophys Res*. Vol. 117, A10201, doi:10.1029/2012JA017703, 2012.

[10] Burke, W. J., G. R. Wilson, C. S. Lin, F. J. Rich, J. O. Wise, *and* M. P. Hagan, Estimating *Dst* indices and exospheric temperatures from equatorial magnetic fields measured by DMSP satellites, *J. Geophys. Res.*, 116, A01205, doi:10.1029/2010JA015310, 2011.

[11] Burke, W. J., L. C. Gentile, and M. P. Hagan, Thermospheric heating by high speed streams in the solar wind, *J. Geophys. Res.,* 115, A06318, doi:10.1029/2009JA014585, 2009.

[12] Burke, W. J., Solar-cycle dependence of solar-wind energy coupling to the thermosphere, *J. Geophys. Res.*, doi:10.1029/2011JA016437, 2011.

[13] Le, G., W. J. Burke, R. F. Pfaff, H. Freudenreich, S. Maus, and H. Lühr, C/NOFS measurements of magnetic perturbations in the low-latitude ionosphere during magnetic storms, *J. Geophys. Res.,* 116, A12230, doi:10.1029/2011JA017026, 2011.

[14] Huang, C. Y., W. J. Burke, J. S. Machuzak, L. C. Gentile, and P. J. Sultan, DMSP observations of equatorial plasma bubbles in the topside ionosphere near solar maximum, *J. Geophys. Res.*, 106*(*A5*),* 8131–8142, *doi:*10.1029/2000JA000319, 2001.

[15] Burke, W. J., O. de La Beaujardière, L. C. Gentile, D. E. Hunton, R. F. Pfaff, P. A. Roddy, Y.-J. Su, and G. R. Wilson, C/NOFS observations of plasma density and electric field irregularities at post-midnight local times, *Geophys. Res. Lett.*, 36, L00C09, doi:10.1029/2009GL038879, 2009.

[16] Su, Y.-J., J. M. Retterer, O. de La Beaujardière, W. J. Burke, P. A. Roddy, R. F. Pfaff Jr., G. R. Wilson, and D. E. Hunton, Assimilative modeling of equatorial plasma depletions observed by C/NOFS, *Geophys. Res. Lett.*, 36, L00C02, doi:10.1029/2009GL038946, 2009.

[17] de La Beaujardière, O., J.M. Retterer, R. Pfaff, R. Roddy, C. Roth, W.J. Burke, Y-J Su, M.C. Kelley, R. Iima, G. Wilson, L.C. Gentile, D.E. Hunton, D.L. Cooke, C/NOFS observations of deep plasma depletions at dawn, *Geophys. Res. Lett.*, *36*, L00C06, doi:10.1029/2009GL038884, 2009.

[18] Huang, C.-S., O. de La Beaujardiere, P. A. Roddy, D. E. Hunton, R. F. Pfaff, C. E. Valladares, *and* J. O. Ballenthin, Evolution of equatorial ionospheric plasma bubbles and formation of broad plasma depletions measured by the C/NOFS satellite during deep solar minimum, *J. Geophys. Res*., 116, A03309, doi:10.1029/2010JA015982, 2011.

[19] Pfaff, R., D. Rowland, H. Freudenreich, K. Bromund, G. Le, M. Acuña, J. Klenzing, C. Liebrecht, S. Martin, W. J. Burke, N. C. Maynard, D. E. Hunton, P. A. Roddy, J. O. Ballenthin, G. R. Wilson, Observations of DC electric fields in the low latitude ionosphere and their variations with local time, longitude, and plasma density during extreme solar minimum, *J. Geophys. Res.*, 115, A12324, doi:10.1029/2010JA016023, 2010.

[20] Gentile, L. C. , W. J. Burke, P. A. Roddy, and J. M. Retterer, Climatology of plasma density depletions observed by DMSP in the dawn sector, *J. Geophys. Res.*, doi:10.1029/2010JA, 2011.

[21] Dao, E., M. C. Kelley, P. Roddy, J. Retterer, J. O. Ballenthin, O. de La Beaujardiere, and Y.-J. Su, Longitudinal and seasonal dependence of nighttime equatorial plasma density irregularities during solar minimum detected on the C/NOFS satellite, *Geophys. Res. Lett*., 38, *L10104,* doi:10.1029/2011GL047046, 2011.

[22] Nishioka, M., Su. Basu, S. Basu, C. E. Valladares, R. E. Sheehan, P. A. Roddy, and K. M. Groves, C/NOFS satellite observations of equatorial ionospheric plasma structures supported by multiple ground-based diagnostics in October 2008, *J. Geophys. Res.*, 116, *A10323, doi:*10.1029/2011JA016446, 2011.

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